Radiated Emissions from Populated Printed Circuit Boards Due to Power Bus Noise

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***Abstract* - Previous studies have demonstrated that power plane pairs in a printed circuit board are capable of generating significant radiated emissions at resonance frequencies if these resonances are not damped by material or component losses. This paper shows that board resonances may be readily damped by component losses. However, radiated emissions from a damped power bus may still exceed FCC or CISPR limits over a broad band of frequencies.**

Keywords- power bus noise; radiated emissions; component loss; cavity model; resonance.

I. INTRODUCTION

For high-speed digital systems, excessive power bus noise can result in functional problems and/or significant radiated emissions [1]-[3]. Recently, a simple closed-form expression was developed to estimate the maximum radiated emissions from a rectangular power bus structure [4]. Equivalent magnetic currents were calculated along the board edge and these currents were used to determine the radiated fields. The results showed that currents as low as a few milliamps could result in unacceptable radiated emissions at frequencies where the power bus was resonant.

This paper investigates the effect of component losses on board resonances and radiated emissions. The radiated emissions from a simple sparsely populated test board are measured and found to exceed FCC and CISPR limits over a broad range of frequencies. The primary source of these emissions is the power bus noise, even though the power bus resonances appear to be well damped by the component loss.

The effects of component loss are further studied using another, more densely populated, test board. Components are systematically removed to determine their relative contribution to the damping of power bus resonances.

Finally, to quantify the effects of the components, a cavity model modified to account for component loss is used to analyze rectangular power bus structures. The results are used to develop a closed-form expression for the maximum radiated fields from populated printed circuit board power bus structures.

II. MEASURED RADIATED EMISSIONS FROM POWER BUS STRUCTURES

The test board shown in Fig. 1 was developed by the UMR EMC Consortium and built by Honeywell to evaluate various sources of printed circuit board EMI. The 28 cm x 21.6 cm board has three 25-MHz crystal oscillators on the left side, which drive various components on the board. The board has 10 layers including 2 power/power-return plane pairs. There are two connectors (P2 and P7) placed on the lower left and the upper right parts of the board as indicated in the figure. SMA connectors were also connected to the board for signal integrity measurements, but they were not used for this study. To minimize the radiation from unidentified sources, power was supplied by a small battery pack mounted to the back of the board.

The measured emissions 3 m from the board without any attached cables are shown in Fig. 2. Although the board is well laid out and has no obvious “antenna” structures such as heatsinks or cables, the radiated emissions are well above FCC and CISPR class B limits. The highest peak occurs between 100 and 200 MHz. The only structures on this board with any electrical size at these frequencies are the power and power return planes.

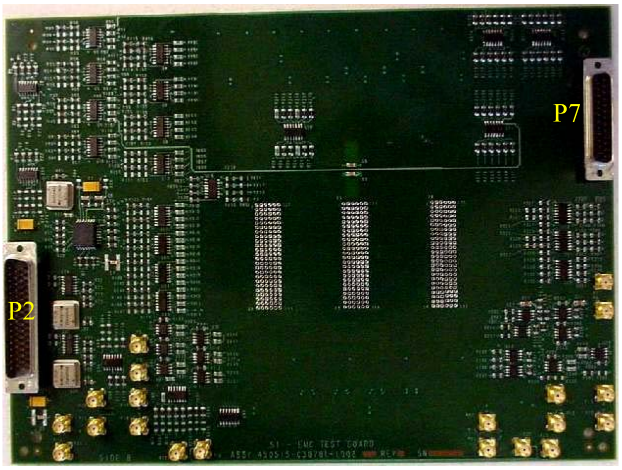

Fig. 1. The Honeywell test board.

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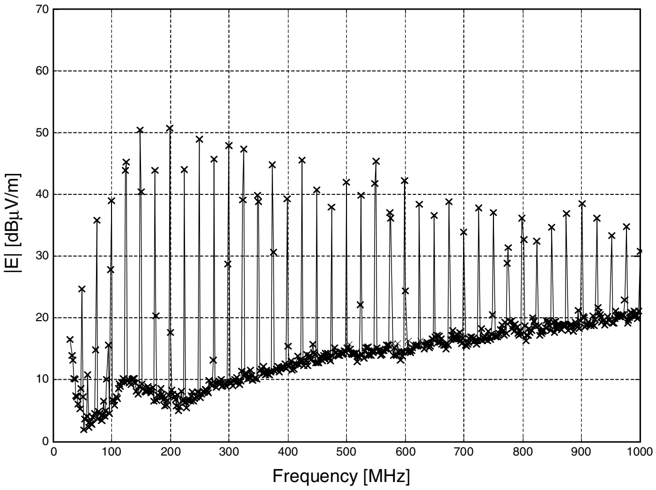


Fig. 2. Radiated emissions from the Honeywell test board with no cables.

M. Leone showed that the power bus radiation from resonant power plane pairs is proportional to the quality factor of the resonances and provided a closed-form expression to estimate the maximum radiation [4]. The quality factor is determined by system losses. Higher losses result in a lower quality factor and reduced emissions. The dominant source of loss in boards with closely spaced power plane pairs is the finite conductivity of the copper planes. However, dielectric losses and component losses are more important in boards with moderately spaced power plane pairs [5].

To illustrate the effects of the component loss, radiated emissions from a second test board were measured with and without components. The "NCMS" test board shown in Fig. 3 has four layers. The two inside layers are power and power return planes. There are 12 identical circuit blocks on the board and each block has 1 clock oscillator, 8 16-bit clock drivers and 34 10-nF decoupling capacitors. The output pins of the clock drivers either connect to an input pin of another driver or are loaded with 10-nF capacitors.

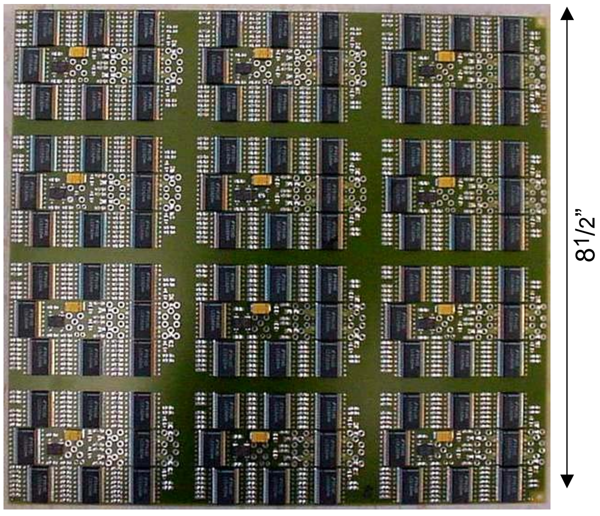
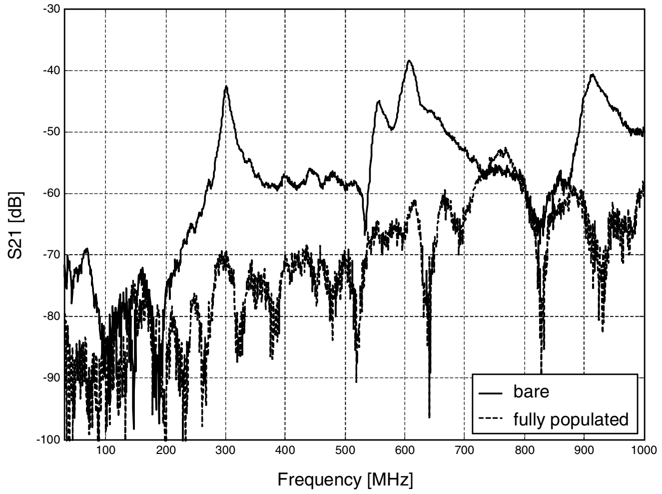
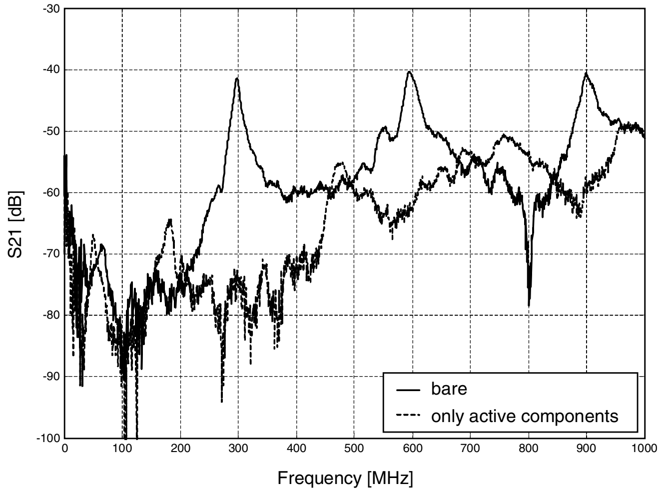


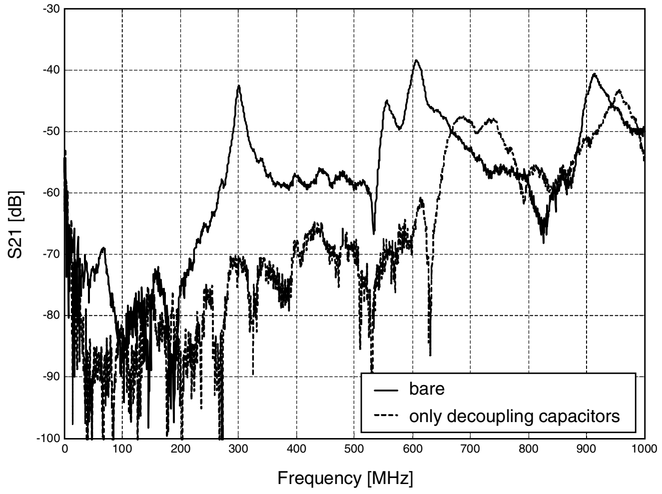
Fig. 3. The NCMS test board



(a) With active components and decoupling capacitors



(b) With active components



(c) With decoupling capacitors

Fig. 4. Measured emissions with and without components

For the results presented here, the NCMS test board's power bus was driven by an external signal source through a SMA connector located at (13 cm, 8 cm) from the left bottom corner. Port 1 of a HP8753D network analyzer was connected to the SMA connector. A receiving antenna located 3 meters away was connected to port 2 of the analyzer. To minimize the effect of common-mode currents induced on the cable, several ferrites were fastened to the cable at various positions.

The radiated fields were first measured with all of the components on the board. The measured magnitude of S_{21} is shown in Fig. 4 (a). The solid line (upper curve) represents the measured emissions from the bare board (no components). The bare board results exhibit peaks with a relatively high quality factor at resonance frequencies. However, the fully populated board does not exhibit these peaks. Overall, the level of the radiated emissions from the fully populated board is much lower.

Fig. 4 (b) shows that the resonances are effectively damped by the active devices alone (i.e. all passive devices removed from the board). Similarly, Fig. 4 (c) shows that the decoupling capacitors are capable of suppressing board resonances even without any active devices connected to the board.

III. CAVITY MODEL OF A RECTANGULAR POWER BUS STRUCTURE WITH COMPONENT LOSS

To model the effect of component loss, a cavity model was used to analyze the power bus structure. The simulated power bus structure is illustrated in Fig. 5. The spacing h between the two planes is assumed to be electrically small. If the length a and width b of the plane are much greater than the dielectric thickness h, the structure can be modeled as a resonant cavity by representing the board edges as perfect magnetic conductor (PMC) walls. Two ports are located at (x_i,y_i) and (x_j,y_j) that have electrically small rectangular cross sections of $(\Delta x_i, \Delta y_i)$ and $(\Delta x_j, \Delta y_j)$, respectively. Since the magnetic fields are perpendicular to the z-direction, the fields inside the cavity can be expressed in terms of summations of modal functions of 2-D TM_z modes. If the dielectric material is low loss and the dimensions of the ports are much smaller than those of the board, the transfer impedance between the two ports is approximately,

$$Z_{ij} = j\omega\mu h\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\chi_{mn}^2\cos\left(k_{xm}x_i\right)\cos\left(k_{yn}y_i\right)\cos\left(k_{xm}x_j\right)\cos\left(k_{yn}y_j\right)}{ab\left(k_{xm}^2+k_{yn}^2+\gamma^2\right)} \tag{1}$$

where $k_{xm}=ma/\pi$, $k_{yn}=nb/\pi$ [6, 7, 8]. The complex propagation constant γ can be written as

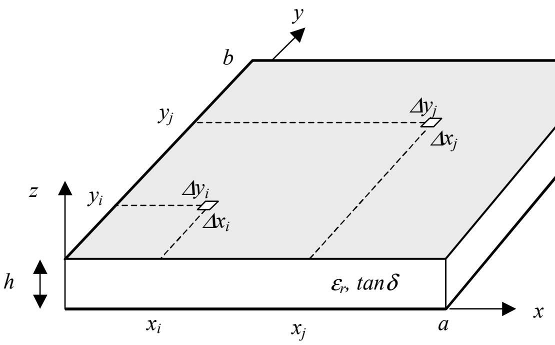


Fig. 5. A rectangular power plane pair

$$\gamma = j\omega\sqrt{\varepsilon\mu}\sqrt{\left(1-j\frac{(1+j)\delta_s}{h}\right)(1-j\tan\delta)} \tag{2}$$

where δ_s is the skin depth of the plane conductors, $tan\delta$ is the loss tangent of the dielectric substrate, and ε is the permittivity of the dielectric substrate [9]. Although this expression for γ does not take into account the effects of radiation and surface wave loss, these losses are negligible in typical power bus structures [9, 10].

The potential at an arbitrary point (x_j,y_j) on the board can be written in terms of the transfer impedance Z_{ij} assuming a filamentary current source I_i at an arbitrary point (x_i,y_i). Using the equivalence principle, the far-field radiated fields can be calculated from the tangential electric and magnetic fields on the surface of an arbitrary volume that contains the radiation sources. Since the electric fields at the board edge are tangential to the surface, the radiated field from the power bus structure can be calculated using the equivalent magnetic current, which is given by

$$\overline{M}_s = \hat{n}\times\overline{E}_z \ . \tag{3}$$

where E_z is the tangential electric field at the edge and n is a unit normal vector pointing out from the board. The far-zone radiated fields can be calculated from the equivalent source currents. Using the free-space Green's function as [4, 10], the far-zone radiated fields are given by

$$\begin{aligned}\overline{E} &= \frac{h}{4\pi}\nabla\times\int_C \overline{M}_s(\overline{r}\,')\frac{e^{-jk_0\left|\overline{r}-\overline{r}\,'\right|}}{\left|\overline{r}-\overline{r}\,'\right|}d\ell' \\ &\approx j\frac{k_0 h}{4\pi}\frac{e^{-jk_0 r}}{r}\int_C\left\{\hat{r}\times\overline{M}_s(\overline{r}\,')\right\}e^{jk_0(\overline{r}\,'\bullet\hat{r})}d\ell'\end{aligned} \tag{4}$$

where the integral path C extends over the periphery of the board. After some mathematical manipulation, E_θ and E_ϕ are given by

$$\begin{aligned}E_\theta \approx j\frac{k_o^3\eta_o hI_i e^{-jk_o r}}{4\pi r}\cdot\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}&\left\{\frac{\chi_{mn}^2\cos(k_{xm}x_i)\cos(k_{yn}y_i)}{ab(k_{xm}^2+k_{yn}^2+\gamma^2)}\cdot\right. \\ \sin\theta\sin\phi\cos\phi\cdot&\left(\frac{\left[1-(-1)^m e^{jk_0 a\sin\theta\cos\phi}\right]\left[1-(-1)^n\cdot e^{jk_0 b\sin\theta\sin\phi}\right]}{k_{xm}^2-k_0^2\sin^2\theta\cos^2\phi}\right. \\ &\left.\left.+\frac{\left[1-(-1)^n e^{jk_0 b\sin\theta\sin\phi}\right]\left[1-(-1)^m\cdot e^{jk_0 a\sin\theta\cos\phi}\right]}{k_{yn}^2-k_0^2\sin^2\theta\sin^2\phi}\right)\right\}\end{aligned} \tag{5}$$

$$\begin{aligned}E_\phi \approx j\frac{k_o^3\eta_o hI_i e^{-jk_o r}}{4\pi r}\cdot\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}&\left\{\frac{\chi_{mn}^2\cos(k_{xm}x_i)\cos(k_{yn}y_i)}{ab(k_{xm}^2+k_{yn}^2+\gamma^2)}\cdot\right. \\ \sin\theta\cos\theta\cdot&\left(\frac{\cos^2\phi\left[1-(-1)^m e^{jk_0 a\sin\theta\cos\phi}\right]\left[1-(-1)^n\cdot e^{jk_0 b\sin\theta\sin\phi}\right]}{k_{xm}^2-k_0^2\sin^2\theta\cos^2\phi}\right. \\ &\left.\left.-\frac{\sin^2\phi\left[1-(-1)^n e^{jk_0 b\sin\theta\sin\phi}\right]\left[1-(-1)^m\cdot e^{jk_0 a\sin\theta\cos\phi}\right]}{k_{yn}^2-k_0^2\sin^2\theta\sin^2\phi}\right)\right\} \ .\end{aligned} \tag{6}$$

Finally, the magnitude of the radiated field can be determined using,

$$|E| = \sqrt{\left|E_\theta\right|^2+\left|E_\phi\right|^2} \ . \tag{7}$$

The maximum radiation at resonance is proportional to the quality factor of the resonance. For high Q resonances, the maximum radiated field is determined primarily by the mode that is excited most efficiently. For a TM_{m0} mode, the strongest equivalent magnetic current sources are located in parallel with the y-axis at $x=0$ and $x=a$. Therefore, the maximum E-field is E_θ on the x-z plane. Similarly, the maximum emissions due to a TM_{0n} mode occur at $\phi=\pi/2$. For the TM_{mn} modes with $m \neq 0$ and $n \neq 0$, the phase of the equivalent magnetic current source alternates. This implies that the maximum field intensity of the TM_{mn} modes is generally less than that of the TM_{m0} or TM_{0n} modes. Therefore, a general expression for the maximum field strength from an unpopulated rectangular board is given by [4]

$$|E|_{\max} \le \frac{120 h I_i}{\varepsilon_r r}\cdot\frac{Q_{bare}(f)}{\min(a,b)} \tag{8}$$

where Q_{bare} is the quality factor of the resonances and can be expressed in terms of conductive and dielectric loss [9].

If the board is heavily populated, the components introduce additional loss and the expression in (2) is no longer adequate. In order to consider the effects of components on a populated board, the component loss can be modeled by introducing an equivalent propagation constant assuming the component loss is distributed uniformly over the board. The new propagation constant, in turn, can be used to obtain a closed-from expression for the maximum radiation from populated power bus structures.

Other researchers have used a radial transmission line approach to derive an equivalent propagation constant for power bus structures with dielectric and conductor loss [9, 11]. Using a similar approach, it is possible to include the effect of component loss in the equivalent propagation constant. Using this new propagation constant, the quality factor of the resonances is given by [12]

$$Q^{-1}(\omega) \approx \tan\delta + \frac{\delta_s}{h} + \frac{N_c R_c}{\omega C_0 (R_c^2 + \omega^2 L_c^2)} \,. \tag{9}$$

Substituting (9) into (8), the radiated field can be calculated. For relatively high Q resonances and the maximum radiated field from a populated rectangular board can be written as

$$\begin{aligned} |E| &\le \frac{120 I_i}{\varepsilon_r \min(a,b)}\cdot\frac{h}{r}\cdot\left(\tan\delta + \frac{\delta_s}{h} + \frac{N_c R_c}{\omega C_0\left(R_c^2 + \omega^2 L_c^2\right)}\right)^{-1} \\ &= \frac{120 I_i}{\varepsilon_r \min(a,b)}\cdot\frac{h}{r}\cdot Q(f) \end{aligned} \,. \tag{10}$$

IV. SIMULATIONS

The maximum radiated field 3.0 m from a populated board was calculated using both the maximum estimate in Equation (10) and a full cavity model to investigate the effect of component loss. The test board simulated was 15.9 cm × 10.8 cm. The spacing between the planes was 0.5 mm and the material between the planes had a dielectric constant of 4.5 and a loss tangent of 0.02. The source was located at the corner in order to fully excite all possible modes. (This is possible in simulations, but not in real implementations.) The components were assumed to be uniformly distributed on the board.

The simulated radiated emissions with uniformly distributed capacitors are shown in Fig. 6. The connection inductance associated with each component was 2.0 nH and the equivalent series resistance (ESR) was 0.3 Ω. These values were chosen to represent a typical configuration [13]. A 1-mA current source was placed at the corner of the board (0,0). The results show that the level of radiated emissions decreases as the number of components increases indicating more loss in the system. The closed-form estimate (10) provides an upper-bound for the maximum radiated emissions predicted by the full cavity model.

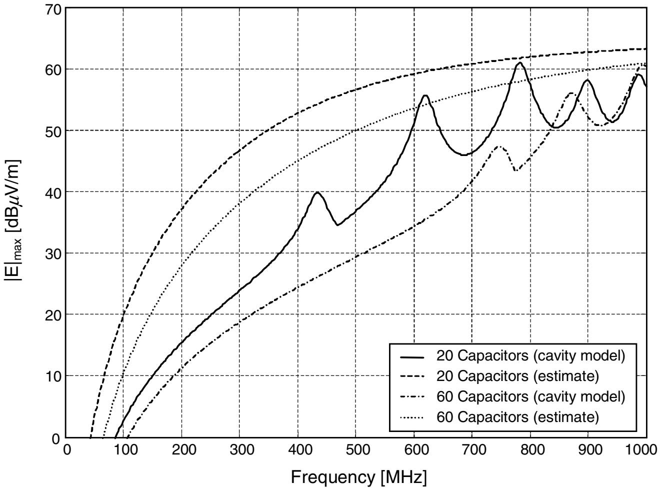


Fig. 6. Simulated emissions with capacitors.

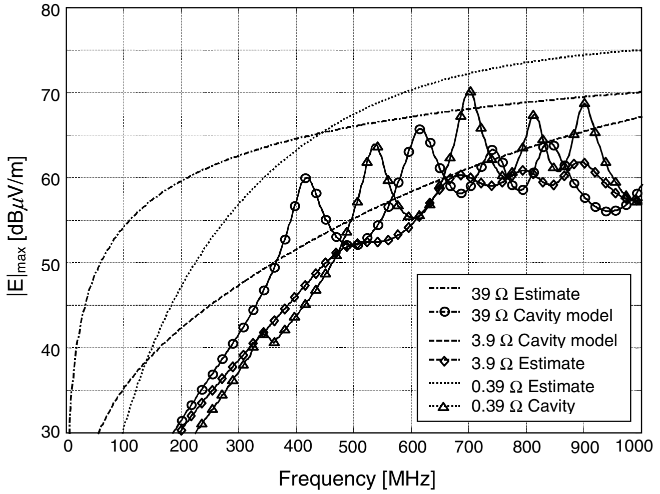


Fig. 7. Simulated emissions with resistors.

In order to illustrate the effect of the ESR value, another set of simulations was performed using resistors instead of capacitors. These results are shown in Fig. 7. The ESL of the connection was assumed to be 1.4 nH and, in this case, the 1-mA current source was located at (4.6 cm, 8.1 cm). The simulations show that the quality factor of the resonance is relatively high when the resistor value is 39 Ω. The quality factor is also high when the resistor value is 0.39 Ω. But with a resistance of 3.9 Ω, the quality factor is lower and the resonances are dampened more efficiently. This is consistent with the fact that maximum energy is delivered to the resistor when the resistance is equal to the magnitude of the inductive reactance [14]. For the given inductance of 1.4 nH, the corresponding reactance is on the order of several ohms at hundreds of megahertz. Since the power bus impedance is also in the range of several ohms, the 3.9-Ω resistors damp the power bus resonances most effectively.

V. CONCLUSION

Radiated emissions from rectangular power bus structures were investigated. Experiments showed that direct radiation from the power bus may cause significant radiation. A cavity model coupled with the equivalence principle can be used to calculate the radiated field intensity. In order to consider the effects of components on the board, the wave propagation constant within the cavity can be modified and a simple expression for the maximum radiated emissions can be derived. Simulated results using a complete cavity model were compared to results obtained using this simple closed-form expression. Both the measured and simulated results suggest that component loss on heavily populated boards is likely to damp power bus resonances. However, power bus emissions can still present radiated EMI problems even when these resonances are damped.

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